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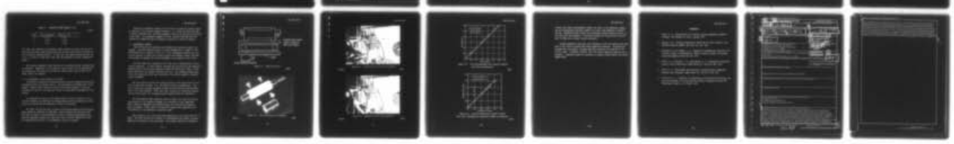

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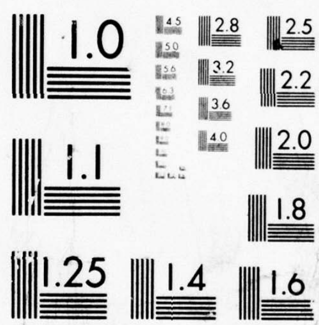

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CSD 2624-ISR-1

ROTATING VALVE FOR VELOCITY COUPLED COMBUSTION RESPONSE MEASUREMENTS

February 1978

Contract No. F49620-77-C-0048

Prepared for

DIRECTOR OF AEROSPACE SCIENCES
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
BOLLING AIR FORCE BASE
DISTRICT OF COLUMBIA 20332

by
R. S. Brown

CHEMICAL SYSTEMS DIVISION

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ILLUSTRATIONS

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NOMENCLATURE

a	sonic velocity
A	acoustic admittance
D	integration constant
E	integration constant
f	frequency
k	see equation 3
K{ }	Kummer Function
L	chamber length
m	velocity coupling parameter
M	Mach No.
q	chamber perimeter
r	see equation 3
R	response function
S	area
Z	dimensionless chamber length

Greek

α	damping
ϵ	acoustic pressure
ω	dimensionless flame temperature oscillation

Subscripts

o	at Z=0
1	at Z=1
b	burning surface
c	chamber
v	valve, velocity

Superscripts

-	time average
'	oscillating component

ABBREVIATIONS

AFOSR	Air Force Office of Scientific Research
AFRPL	Air Force Rocket Propulsion Laboratory
AIAA	American Institute of Aeronautics and Astronautics
CSD	Chemical Systems Division
NASA	National Aeronautics and Space Administration

1.0 INTRODUCTION AND SUMMARY

Coupling between the combustion process and the acoustics of the combustion chamber are important factors determining combustion stability of a solid propellant rocket. This coupling results because the combustion process reacts to both the local acoustic pressure and the local acoustic velocity. Because of the complexity of both processes, they cannot be totally characterized analytically; therefore, laboratory test data are needed in making analytical combustion stability predictions. One attractive test method conceived by CSD is the rotating valve apparatus. CSD has conducted two programs under AFRPL contract No. F04611-72-C-0007 and F04611-74-C-0045 to develop and demonstrate the rotating valve method of measuring the pressure coupled combustion response of solid propellants. Measurements have been made using both aluminized and nonaluminized propellant formulations in a single rotating valve apparatus. The results show agreement with T-burner measurements when the T-burner vent term is taken to be zero. In addition, reproducible operation of the apparatus has been demonstrated at pressures up to 1,500 psi with propellants containing as much as 18% aluminum.

The rotating valve apparatus also offers the advantage of adaptability to obtain velocity coupled response. Velocity oscillations of controlled frequency and amplitude can be generated in the test motor by simultaneously operating a rotating valve at each end of the motor, 180° out of phase. In this configuration, velocity coupling dominates, and the effects of other processes, such as pressure coupling, are minimized. With this modification, the rotating valve method offers the potential for experimentally and quantitatively investigating many characteristics of velocity coupling which have been postulated by purely analytical arguments. The nature of these characteristics determine the manner in which velocity coupling is incorporated into the overall combustion stability analysis of a solid propellant rocket motor; thus, experimental evaluation of velocity coupling characteristics is essential.

Under AFOSR contract No. F49620-77-C-0048, CSD investigated the two-valve approach for measuring velocity coupling characteristics. Analytical studies accomplished under this contract have developed a thorough mathematical analysis of the transient ballistics by solving the transient mass, momentum, and energy equations and by including velocity coupling, as well as pressure coupling, particle damping, flow turning, and nozzle losses in the analysis. The analysis has been compared to known solutions appropriate to specific situations. Studies have been conducted to explore its limitations and to estimate the effects of experimental uncertainties. Approximate solutions have been developed which permit the direct derivation of velocity response functions from experimental data. In addition, this analysis has suggested a method for simultaneously deriving quantitative information on particle damping and for increasing the upper frequency of the pressure coupled rotating valve by a factor of two. These last two developments were not expected at the initiation of the program and each represents a potentially significant advance in the technology.

Concurrently, experimental apparatus was constructed, and its performance compared with predictions under controlled cold flow conditions. Agreement between theory and experiment was demonstrated under pressure coupled test conditions. Analysis of the initial data, in conjunction with the analytical model, shows control of the phase angle between the two valves is important to insure proper performance of the apparatus. Studies in this area are in progress and are directed toward defining the degree of control required and developing proper control and calibration methods.

2.0 TECHNICAL STUDIES

The basic velocity coupled rotating valve apparatus has two identical valves, one at each end of the test motor as shown in figure 2-1,. One or more conventional nozzles are used to control the steady-state pressure. The instantaneous area of each valve, (figure 2-1) may be represented by the sum of a steady-state component and an oscillating component.

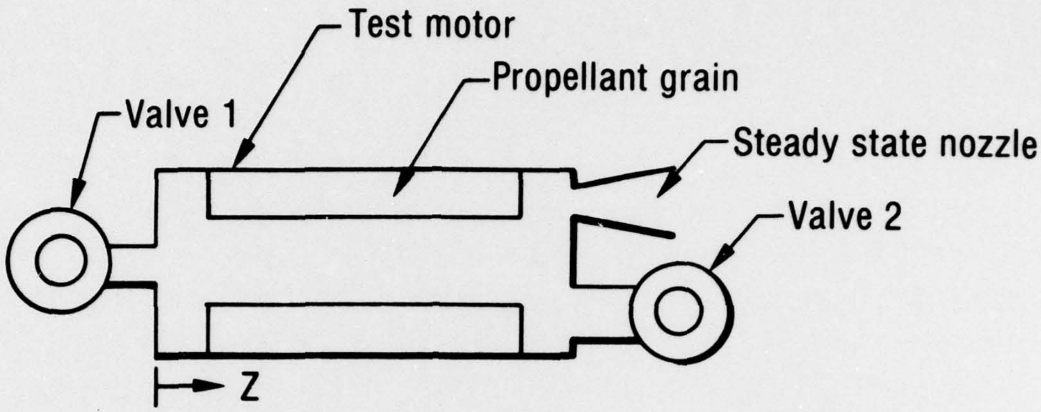
The central feature of the apparatus is the control of the phase between the area oscillations of the two valves. If the two valves are in phase, the oscillating components add, as shown in figure 2-2. The resulting behavior is dominated by pressure coupling effects. If the valves are 180° out of phase, the area oscillation produced by one valve exactly cancels that produced by the other valve. There is no net area oscillation to provide pressure coupling; however, significant velocity oscillations in the test motor are produced, because the venting of combustion gas alternates between the two ends of the motor. These velocity oscillations couple with the combustion to produce burning rate oscillations. With a constant net vent area, these burning rate oscillations produce pressure oscillations which reflect the coupling process. Thus, operating the two valves 180° out of phase offers the potential for studying velocity coupling in a manner which minimizes pressure coupled contributions.

CSD is currently conducting analytical and experimental studies under contract No. F49620-77-C-0048 to explore the applicability of the dual rotating valve apparatus for measuring velocity coupled combustion response functions.

The basic objectives of the current program are to:

(1) Improve and modify the analytical model for the transient ballistics of the two valve apparatus;

(2) Define the sources and magnitude of potential uncertainties in the data analysis procedure;



$$A_{v_1} = \bar{A}_{v_1} + \hat{A}_{v_1} \exp(i2\pi ft) \qquad A_{v_2} = \bar{A}_{v_2} + \hat{A}_{v_2} \exp(i2\pi ft)$$

Figure 2-1. Valve Layouts for Velocity Response

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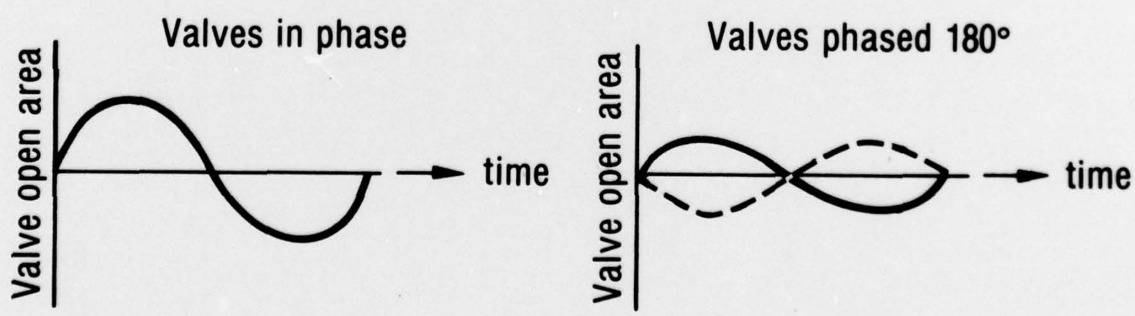

Figure 2-2. Valve Driving

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(3) Design and construct a dual rotating valve apparatus;

(4) Verify the analytical model under cold flow conditions and experimentally explore additional sources of uncertainty; and

(5) Conduct limited combustion tests to evaluate performance of the apparatus, the quality of the resulting response functions, and ability to study the effects of varying propellant formulation and mean flow velocity.

Studies have been conducted in each of these areas and specific results are summarized in the following paragraphs.

2.1 ANALYTICAL STUDIES

Initial evaluation of the method assumed that momentum and energy effects could be neglected so that the transient mass balance described the system behavior(1). The validity of these assumptions is suspect in the velocity coupled mode; therefore, a more detailed and less restricted analysis is required. Development of the expanded mathematical model requires the solution of the transient ballistic equations for mass, momentum, and energy.

2.1.1 Model Development

The basis of these expanded analytical studies is the one-dimensional equations of motion, in conjunction with the ideal gas law. After linearization and rearrangement one obtains

$$\frac{\partial \epsilon'}{\partial Z} + \frac{\partial M'}{\partial \tau} + \frac{\partial (\bar{M} \cdot M')}{\partial Z} + \sigma' - F' = 0 \qquad (1)$$

for the momentum equation and

$$\frac{\partial \varepsilon'}{\partial \tau} + \bar{M}\frac{\partial \varepsilon'}{\partial Z} + \frac{\partial M'}{\partial Z} = \left(\frac{A_b qL}{S}\right)\varepsilon' + \left(\frac{\bar{M}_b qL}{S}\right)\left(R_b + \omega_f\right)_v \frac{\bar{M}\cdot M'}{|\bar{M}|} \qquad (2)$$

for the energy equation.

These equations can be transformed to a Kummers equation[2].

$$r \frac{d^2\varepsilon'}{dr^2} + \left\{\frac{1}{2} - r\right\} \frac{d\varepsilon'}{dr} - k\varepsilon' = 0 \tag{3}$$

The solution then becomes[3]

$$\varepsilon' = D\,K\left\{k,\ \frac{1}{2},\ r\right\} + E r^{\frac{1}{2}}\,K\left\{k + \frac{1}{2},\ \frac{3}{2},\ r\right\} \tag{4}$$

The two constants of integration can be evaluated from the nozzle flow equations at each end of the chamber.

The solution of these equations was verified in several ways. First at low frequencies, the equations should reduce analytically to the equations derived for the pressure coupled rotating valve[4,5], assuming no velocity response and driving from only one valve. At low frequencies, the Kummer functions approach unity. This leads analytically to the equations reported in references [4,5] for the case of one valve and for both valves operating in phase.

Second, this model should predict the correct behavior when the combustor is driven at frequencies near the natural acoustic frequencies. Thus, the frequency difference at the half- power amplitudes (i.e., 0.707 x the peak amplitudes) would be related to the overall system damping of the self-excited system by the expression.

$$\frac{\alpha}{f} = \frac{\pi \Delta f}{f} \tag{5}$$

The left side can be evaluated independently from Culick's solutions while the right side can be evaluated from numerical solutions of the model. This comparison has been made in three cases shown in table 2-1.

TABLE 2-1. COMPUTED SYSTEM DAMPING ($-\alpha/f$)

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Case	Culick Analysis	Equation (4)
1	0.112	0.117
2	0.155	0.156
3	0.102	0.108

The first case contained only pressure coupled effects and used only one valve. The second and third cases incorporated both pressure and velocity coupling, as well as particle damping effects. In case two, the response functions were low (i.e., 0.2) while in case three, they were approximately an order of magnitude higher.

The excellent agreement found between the two methods further substantiates the analysis. Examination of the numerical results shows that the amplitudes of the pressure at both ends of the burner are nearly equal, but are 180^{o} out of phase, exactly as expected.

2.1.2 Development of Data Reduction Procedure

The analysis presented the preceding section predicts pressure and velocity performance given the response values. The data analysis procedure must do the opposite, namely produce response values from measured pressures. Since the responses are implicit, the equations cannot be conveniently rearranged for this purpose.

An approximate solution to the energy equation, which is explicit in the velocity response, was developed by assuming the velocity oscillations are invariant with position and the pressure is linear with position.

The exact solution was used to predict oscillating pressures and velocities using combustion responses for ANB 3066. These pressures and velocities were then used as inputs to the approximate solution to simulate experimental data. Excellant agreement between the derived and input velocity response was found for frequencies below 25% of the fundamental acoustic frequency.

Similarly the momentum equation can be solved to provide an equation which is explicit in the particle damping parameter, τd. Using the exact solutions to predict simulated data, excellent agreement between the input and the derived τ_d was found. This agreement suggests the dual rotating valve may have the capability of measuring particle damping in addition to velocity response.

2.2 EXPERIMENTAL STUDIES

A dual rotating valve apparatus was designed and constructed under this program. The basic apparatus layout is shown schematically in figure 2-3 and photographically in figures 2-4 thru 2-6. This arrangement provides the flexibility required to study both velocity coupled and pressure coupled configurations simply by changing the holes arrangement of the graphite rotor sleeve.

Cold flow tests were conducted as the first step in experimentally evaluaing this apparatus. In these studies, nitrogen was injected into the combustion chamber and the two auxiliary chambers through individual sonic chokes. Under these conditions, the response functions are zero. The discharge coefficients of all three exhaust nozzles were evaluated by calibration against a standard venturi flowmeter.

The first series of tests was conducted using a rotor sleeve where the two rows of holes were in phase, i.e., the pressure coupled configuration. Figure 2-7 shows the excellent agreement between the predicted and observed amplitude in all three chambers. These tests were conducted at frequencies between 100 and 250 Hz using the clockwise-counterclockwise method of reference 5.

The corresponding phase comparison shown in figure 2-8, used the oscillating pressure in the combustion chamber as a reference in this comparison. Again, excellent agreement was obtained between the predicted and observed phase difference. These results are important because they demonstrate that the operation of the apparatus is basically sound.

Next a series of cold flow tests were conducted with the valves 180° out of phase. The first studies were directed to investigating the effects of mechanmechanical tolerances on the phase angle. The studies reported in reference 5

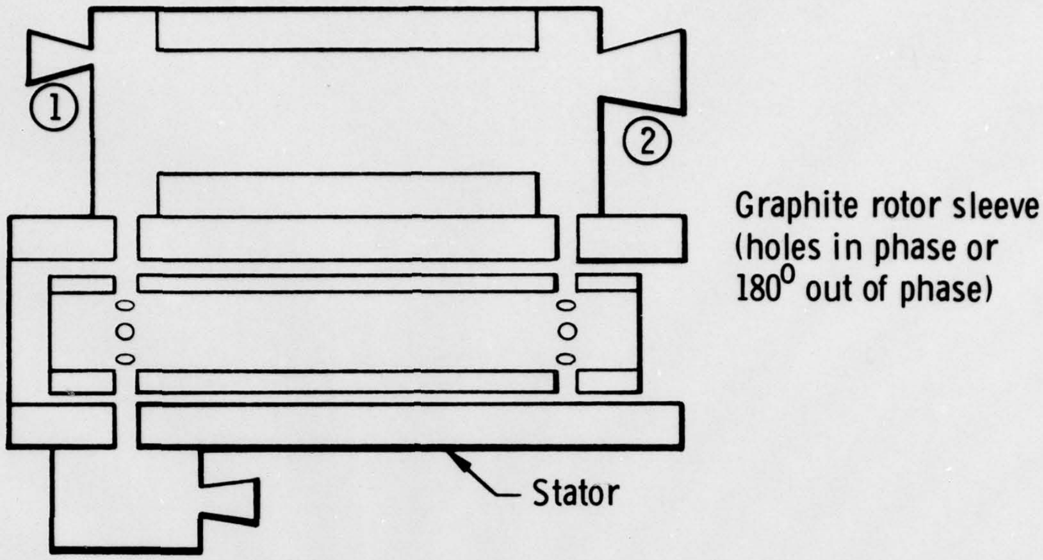

Figure 2-3. Apparatus Layout

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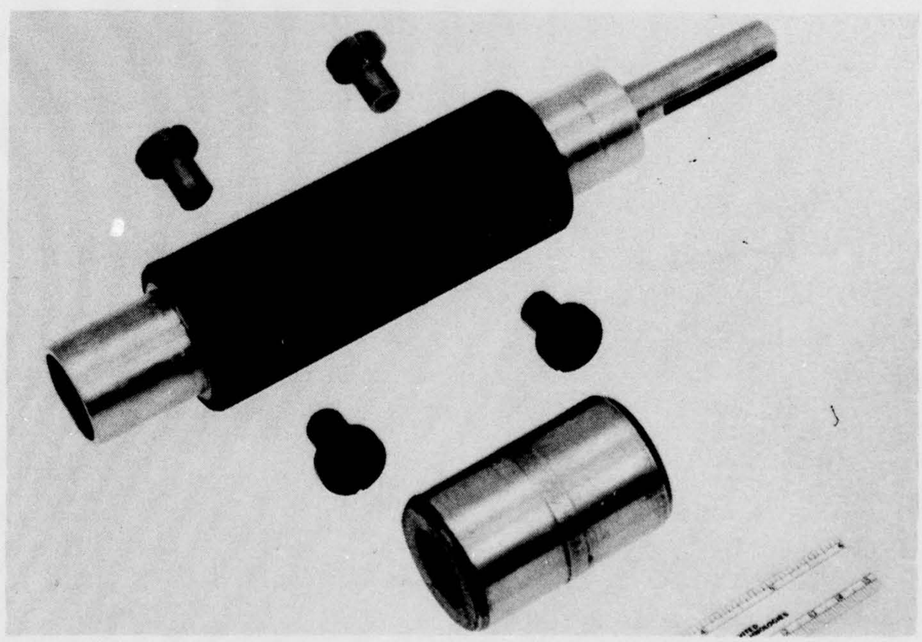

Figure 2-4. Dual Rotating Valve Components

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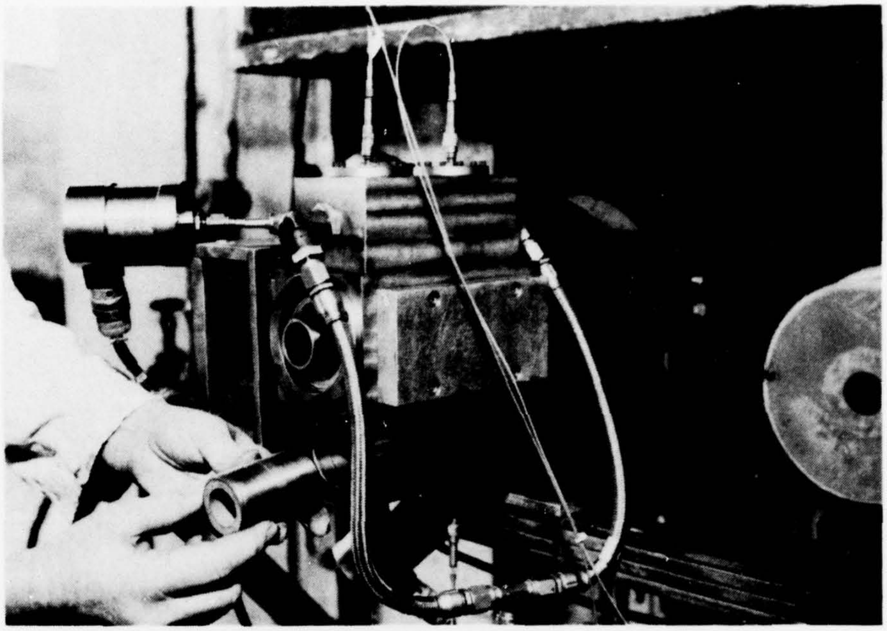

Figure 2-5. Propellant Grain and Valve Assembly

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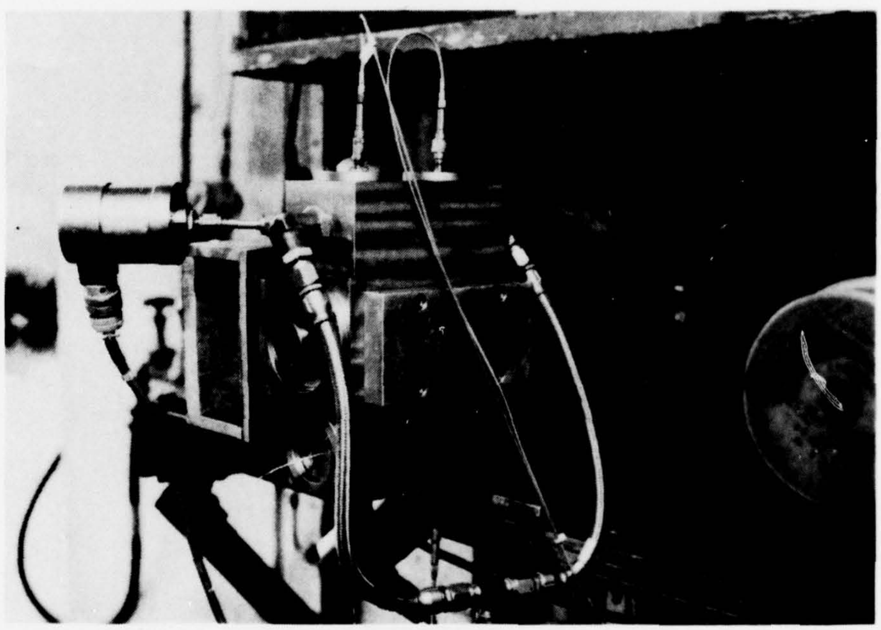

Figure 2-6. Assembled Rotary Valve Apparatus

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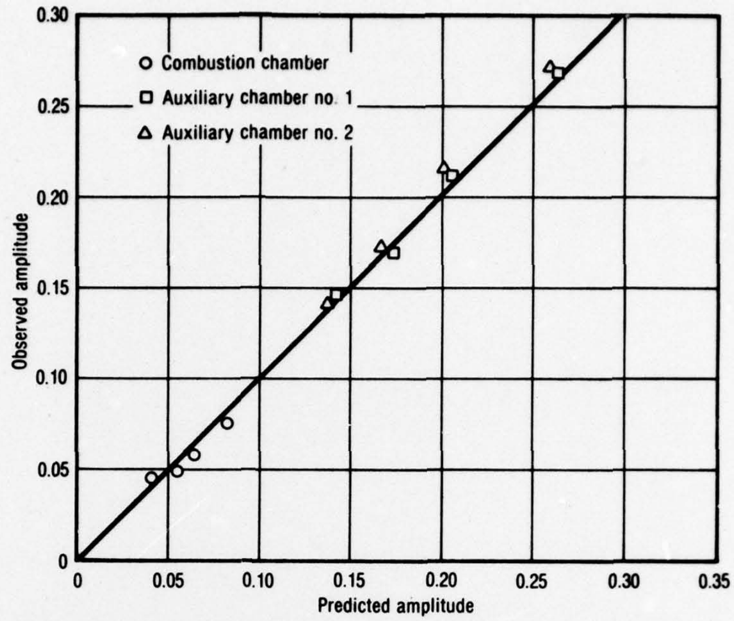

Figure 2-7. Cold Flow Amplitude Data Pressure Coupled Dual Valve Configuration

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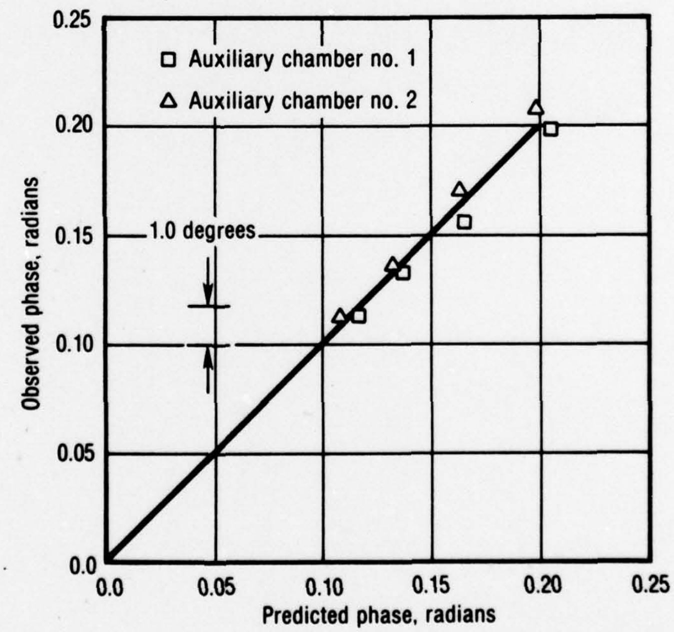

Figure 2-8. Cold Flow Phase Data Pressure Coupled Dual Valve Configuration Combustion Chamber as Reference

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indicate that phase misalignments between the vents in the combustion chamber and the corresponding auxiliary chamber can result from mechanical tolerance buildup. Minimizing these effects by maintaining extreme tolerance control is both difficult and expensive. Alternative methods for resolving this problem must be found and are under current evaluation.

Limited combustion tests have been conducted to test the apparatus performance in the velocity coupled mode using aluminized propellant. No mechanical problems were encountered, although amplitude modulation was observed in the initial tests. It appears, however, that the current apparatus operates satisfactorily. Combustion tests are currently in progress using sleeves with evenly spaced holes.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Quanitative measurement of the velocity coupled response function is required for quantitative predictions of the combustion stability characteristics of rocket motors. Velocity oscillations of controlled frequency and magnitude can be generated in a test motor by simultaneously operating a rotating valve at each end of the motor, 180 deg out of phase. Analytical studies have developed a transient ballistics model for the one dimensional flow in the test motor. The analysis incorporates velocity coupling, pressure coupling, and particle damping effects. The model reduces to previously developed approximate solutions of the mass, momentum, and energy equations. In addition, the next page

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) analysis predicts the stability characteristics for one dimensional acoustic oscillations. Approximate solutions were developed for deriving velocity coupled response functions and potentially particle damping parameters from experimental pressure measurements. Experimental tests have shown cold flow ballistics are corrently modeled by the analysis when the two valves are in phase. Thus, the internal geometries are ballistically sound. Velocity coupled cold flow tests show significant pressure amplitude modulations which were traced to mechanical tolerance buildups. Methods are under study for reducing this buildup and for eliminating residual tolerance effects by appropriate cold flow calibrations.